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AGN Winds and the Black-Hole - Galaxy Connection

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Abstract.

During the last decade, wide-angle powerful outflows from AGN, both on parsec and kpc scales, have been detected in many galaxies. These outflows are widely suspected to be responsible for sweeping galaxies clear of their gas. We present the analytical model describing the propagation of such outflows and calculate their observable properties. Large-scale AGN-driven outflows should have kinetic luminosities $\sim \eta L_{\text{Edd}}/2 \sim 0.05 L_{\text{Edd}}$ and momentum rates $\sim 20 L_{\text{Edd}}/c$, where L_{Edd} is the Eddington luminosity of the central black hole and $\eta \sim 0.1$ its radiative accretion efficiency. This creates an expanding two-phase medium in which molecular species coexist with hot gas, which can persist after the central AGN has switched off. This picture predicts outflow velocities $\sim 1000 - 1500 \text{ km s}^{-1}$ and mass outflow rates up to $4000 \text{ M}_{\odot} \text{ yr}^{-1}$ on kpc scales, fixed mainly by the host galaxy velocity dispersion (or equivalently black hole mass). We compare our prediction with recent observational data, finding excellent agreement, and suggest future observational tests of this picture.

1. Introduction

Recently, two sets of observations have allowed us to gain a better understanding of the interaction between AGNs and their host galaxies. These are observations of high-velocity wide-angle winds emanating from the vicinity of the SMBH, which have been detected in a large fraction of AGNs (Tombesi et al. 2010a,b); and detection of kpc-scale quasi-spherical outflows in active galaxies, with enough power and mass flow to sweep their host galaxies clear of gas (Feruglio et al. 2010; Rupke & Veilleux 2011; Sturm et al. 2011; Riffel & Storchi-Bergmann 2011a,b). These outflows have kinetic power equal to a few percent of the Eddington luminosity of the central black hole and their momentum flow rate is approximately an order of magnitude greater than L_{Edd}/c .

In this paper, we show how the two types of flows can be explained within the framework of AGN wind feedback. Radiation pressure from an accreting SMBH expels gas in form of a wind from the nucleus (e.g. Pounds et al. 2003a,b), which then pushes the ambient gas in the host galaxy and produces an outflow. In recent work (King et al. 2011; Zubovas & King 2012) we have shown that large-scale energy-driven flows (see Section 3) can indeed drive much of the interstellar gas out of a galaxy bulge on a dynamical timescale $\sim 10^8 \text{ yr}$, leaving it red and dead. The remaining mass of the bulge is then similar to the value set by the observed black-hole – bulge-mass relation (e.g. Häring & Rix 2004). The observable features of such outflows – velocities, kinetic powers and mass and momentum flow rates – are consistent with observations. Therefore AGN outflows appear capable of sweeping galaxies clear of gas.

2. Close to the SMBH – winds

Radiation pressure from an AGN accreting at close to its Eddington limit can expel gas from the vicinity of the nucleus with a momentum rate

$$\dot{M}_w v_w = \frac{L_{\text{Edd}}}{c}, \quad (1)$$

as the wind on average has scattering optical depth ~ 1 and absorbs all of the radiation momentum. This creates a mildly relativistic diffuse wind ($\dot{M}_w \sim \dot{M}_{\text{Edd}}$ and $v_w \sim \eta c \sim 0.1c$, where $\eta \simeq 0.1$ is the accretion radiative efficiency King 2003; King & Pounds 2003). Observations of blueshifted X-ray iron absorption lines corresponding to velocities $\sim 0.1c$ (e.g. Pounds et al. 2003a,b; Tombesi et al. 2010a,b) reveal that the majority of quasars produce such winds. The winds have momentum and energy rates

$$\dot{P}_w \sim \frac{L_{\text{Edd}}}{c}; \quad \dot{E}_w = \frac{1}{2} \dot{M}_w v_w^2 \sim 0.05 L_{\text{Edd}}. \quad (2)$$

3. Out in the galaxy – outflows

It is clear that the wind has enough kinetic power to drive the observed large scale outflow, provided that it can efficiently transfer this power to the ISM. In order for this to happen, two conditions must be satisfied. First, most of the sightlines from the SMBH must be covered with diffuse medium. Second, the wind cannot cool efficiently. As the wind hits the ISM, it shocks and heats to $T \sim 10^{11}$ K. At this temperature, the most efficient cooling process is inverse Compton scattering of the photons in the AGN radiation field (Ciotti & Ostriker 1997). The efficiency of this process drops with increasing shock radius, thus the cooling timescale increases as R^2 . Since the outflow velocity does not depend strongly on radius (King 2010; King et al. 2011), the flow timescale only increases as R . Therefore, there is a critical radius, $R_{\text{cool}} \sim 1$ kpc, within which the shock can be cooled efficiently, whereas outside most of its energy is retained and transferred to the outflow. The two cases are called momentum-driven and energy-driven flows, respectively; their salient features are shown schematically in Figure 1.

3.1. Momentum-driven outflow

An efficiently cooled shocked wind gas is compressed to high density and radiates away almost all of its original kinetic energy, retaining and communicating only its pressure, which is equal to the pre-shock ram pressure $\dot{P}_w \simeq L_{\text{Edd}}/c \propto M$, to the host ISM.

For an isothermal ISM density distribution with velocity dispersion σ and gas fraction f_c (the ratio of gas density to background potential density) the behaviour of the flow depends on the black hole mass M (King 2003, 2010). For $M < M_\sigma$, where

$$M_\sigma = \frac{f_c \kappa}{\pi G^2} \sigma^4 \simeq 4 \times 10^8 M_\odot \sigma_{200}^4, \quad (3)$$

with $f_c = 0.16$ and $\sigma_{200} = \sigma/(200 \text{ km s}^{-1})$, the wind momentum is too weak to drive away the swept-up ISM, and the flow stalls. For $M > M_\sigma$ the wind drives the swept-up ISM far from the nucleus, quenching its own gas supply and further accretion. Therefore, M_σ represents an approximate upper limit to the SMBH mass distribution (see Power et al. 2011, for more details). The calculated mass is very similar to that obtained from observations of the $M - \sigma$ relation, despite having no free parameter.

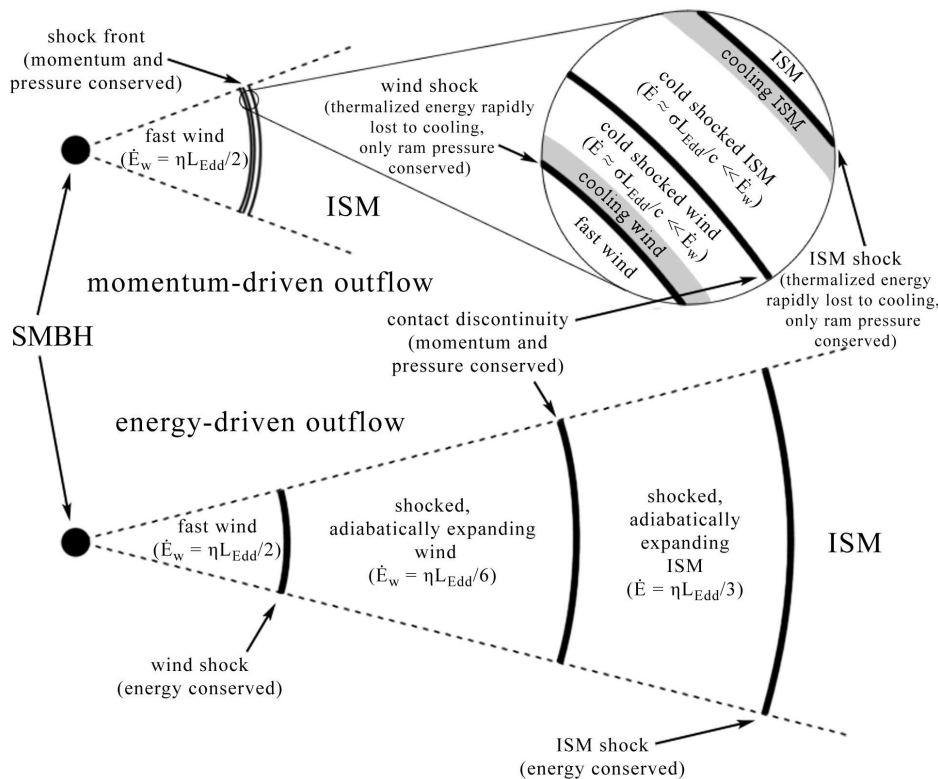


Figure 1. Schematic picture of AGN outflows. A wind with $v_w \sim 0.1c$ impacts the ISM of the host galaxy, producing a shock on either side of the contact discontinuity. Within ~ 1 kpc of the nucleus (top), the shocks cool rapidly and radiate away most of their energy, leading to outflow kinetic energy $\sim (\sigma/c)L_{\text{Edd}}$. In an energy-driven outflow (bottom), the shocked regions expand adiabatically, communicating most of the kinetic energy of the wind to the outflow, which is then able to sweep the galaxy clear of gas.

3.2. Energy-driven outflow

A large-scale ($\gtrsim 1$ kpc) outflow becomes energy driven. It is essentially adiabatic, and has the wind energy rate, i.e. $\dot{E}_{\text{out}} \simeq \dot{E}_w \sim 0.05L_{\text{Edd}}$ (from Equation 2). The hot bubble's thermal expansion makes the driving into the host ISM more vigorous than in the momentum-driven case. Observed galaxy-wide molecular outflows must be energy-driven, as demonstrated directly by their kinetic energy content (cf. Equation 2). The adiabatic expansion of the shocked wind pushes the swept-up interstellar medium in a 'snowplow'. In King et al. (2011) we derive the analytic solution for the expansion of the shocked wind in a galaxy bulge with an isothermal mass distribution. With AGN luminosity lL_{Edd} , all such solutions tend to an attractor

$$\dot{R} = v_e \simeq \left[\frac{2\eta l f_c}{3f_g} \sigma^2 c \right]^{1/3} \simeq 925 \sigma_{200}^{2/3} (l f_c / f_g)^{1/3} \text{ km s}^{-1} \quad (4)$$

until the AGN switches off when the shock is at some radius $R = R_0$. Subsequently, the expansion speed decays with $x = R/R_0 \geq 1$ as

$$\dot{R}^2 = 3\left(v_e^2 + \frac{10}{3}\sigma^2\right)\left(\frac{1}{x^2} - \frac{2}{3x^3}\right) - \frac{10}{3}\sigma^2. \quad (5)$$

In Eq. (4), the current gas fraction f_g may be lower than f_c (cf. Eq. 3). The outflow persists for an order of magnitude longer than the duration of the quasar outburst that is driving it, and reaches radii of $10^4 - 10^5$ pc. It is evident that energy-driven outflows are capable of sweeping gas out of galaxies, quenching further star formation and establishing the SMBH – bulge mass relationship (Power et al. 2011).

3.3. Observable outflow parameters

The solutions (4, 5) describe the motion of the contact discontinuity see Figure 1). Outflows are usually observed in molecular gas, which is embedded in the outflowing shell (see Zubovas & King 2012, for more details), which moves with velocity

$$v_{\text{out}} = \frac{\gamma + 1}{2}\dot{R} \simeq 1230\sigma_{200}^{2/3}\left(\frac{lf_c}{f_g}\right)^{1/3} \text{ km s}^{-1} \quad (6)$$

from adiabatic shock conditions, using $\gamma = 5/3$, and the mass outflow rate is

$$\dot{M}_{\text{out}} = \frac{dM(R_{\text{out}})}{dt} = \frac{(\gamma + 1)f_g\sigma^2}{G}\dot{R} = \frac{\eta(\gamma + 1)f_g}{4}\frac{\dot{R}c}{f_c\sigma^2}\dot{M}_{\text{Edd}}, \quad (7)$$

assuming $M = M_\sigma$. If the AGN luminosity is still close to Eddington and $f_g = f_c$, the mass loading factor ($f_L \equiv \dot{M}_{\text{out}}/\dot{M}_{\text{Edd}}$) and mass outflow rates are

$$f_L = \left(\frac{2\eta c}{3\sigma}\right)^{4/3}\left(\frac{f_g}{f_c}\right)^{2/3}\frac{l^{1/3}}{\dot{m}} \simeq 460\sigma_{200}^{-4/3}\frac{l^{1/3}}{\dot{m}}; \quad \dot{M}_{\text{out}} \simeq 3700\sigma_{200}^{8/3}l^{1/3} \text{ M}_\odot \text{ yr}^{-1}. \quad (8)$$

If the central quasar is no longer active, \dot{M}_{out} is lower by \dot{R}/v_e , with \dot{R} given by Eq. (5).

One can show from Equations (6) and (8) that $\dot{M}_{\text{out}}v_{\text{out}}^2/2 \simeq 0.05L_{\text{Edd}}$, i.e. most of the wind kinetic energy is transferred to the outflow, as expected for energy driving (more precisely, while the quasar is active, the outflow contains 2/3rds of the total energy). We can also derive an expression for the momentum flow rate \dot{P} in the outflow:

$$\dot{P}_{\text{out}} = \frac{L_{\text{Edd}}}{c}f_L^{1/2} \sim 20\sigma_{200}^{-2/3}l^{1/6}\frac{L_{\text{Edd}}}{c}. \quad (9)$$

4. Discussion

We see that in principle, large-scale wide-angle outflows driven by a mildly relativistic wind launched by the AGN radiation pressure can sweep galaxies clear of gas. The observable properties of such outflows are typical velocities $v_{\text{out}} \sim 1000 - 1500 \text{ km s}^{-1}$ and mass flow rates up to $\dot{M}_{\text{out}} \sim 4000 \text{ M}_\odot \text{ yr}^{-1}$ (Equations (6) and (8)). The outflows should have mechanical luminosities $\dot{E}_{\text{out}} \sim (\eta/2)L_{\text{Edd}} \sim 0.05L_{\text{Edd}}$, but (scalar) momentum rates $\dot{P}_{\text{out}} \sim 20L_{\text{Edd}}/c$, consistent with observations (see Table 1).

Table 1. Outflow parameters: observation versus prediction for a sample of AGN

Object	\dot{M}_{out}	v_{out}	$\frac{\dot{E}_{\text{out}}}{0.05L_{\text{bol}}}$	$\frac{\dot{M}_{\text{out}}v_{\text{out}}c}{L_{\text{bol}}}$	f_L	$\dot{M}_{\text{pred.}}$	$v_{\text{pred.}}$	$f_{L,\text{pred.}}$
Mrk231 ^(a)	420	1100	0.66	18	490	880	810	840
Mrk231 ^(b)	700	750	0.51	20	820	880	810	840
Mrk231 ^(c)	1200	1200	1.0	25	1400	1150	1060	1110
IRAS 08572+3915 ^(c)	970	1260	2.1	50	1200	950	875	910
IRAS 13120–5453 ^(c)	130	860	0.88	31	1080	220	610	1870

First two columns: observed mass flow rate (in $M_{\odot} \text{ yr}^{-1}$) and velocity (in km s^{-1}) of large-scale outflows in molecular (Mrk231, IRAS 08572+3915 and IRAS 13120–5453) and warm ionised gas (Mrk1157). Middle three columns: quantities derived from observations. Last three columns: mass flow rate, velocity and mass loading factor derived from our equations (6) and (8). All derived quantities show good agreement with those observed and with each other.

References: ^a - Rupke & Veilleux (2011); ^b - Feruglio et al. (2010); ^c - Sturm et al. (2011).

Such outflows leave several observable signatures. Cold gas clumps entrained within the shell produce the observed molecular emission. The inner wind shock accelerates cosmic ray particles, which can emit synchrotron radiation in the radio band and produce gamma rays when interacting with the ISM. These signatures resemble those of the gamma-ray emitting bubbles in our Galaxy recently discovered by *Fermi* (Su et al. 2010), which can be explained as relics of a short quasar outburst about 6 Myr ago (Zubovas et al. 2011, also the contribution by Zubovas to this volume).

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